3. Detector related questions. For BTeV and CKM are there any detector components whose design and construction have significant risks? For each of the upgrades, what are the conditions under which silicon replacement is necessary (please be quantitative regarding the physics impact of no replacement for various luminosity choices)? What would the detector performance and schedule impacts be if the innermost silicon layer near the beam pipe were replaced with the remainder of the detector unchanged?

For BTeV and CKM are there any detector components whose design and construction have significant risks?

The BTeV detector must satisfy demanding requirements to carry out its program of measurements in the challenging environment of the Tevatron. These are described below. However, the succinct answer to this question is that a highly successful program of R&D, begun in 1998, and carried out with the support of the DOE, NSF, INFN (Italy) and IHEP (Russia) has resulted in development of solutions to each challenge. While there are still detailed engineering and cost optimization to complete on some of the subsystems, **the feasibility of each detector component, the trigger, and the data acquisition system have been demonstrated and there are no known show stoppers to the successful construction and operation of the BTeV detector.** In addition, there has already been substantial attention to detector assembly and integration.

The principle challenges to doing B physics at a hadron collider are: the B events are accompanied by a very high rate of background events; the B's are produced over a very large range of momentum and angles; and even in the B events of interest, there is a complicated underlying event so one does not have the stringent constraints that one has, for example, in an e^+e^- machine. These lead to questions about the triggering, tagging, and reconstruction efficiency and the background rejection that can be achieved at a hadron collider. In particular BTeV must have

- A very efficient trigger for a wide variety of "hadron-only" final states with "hadron-only" flavor tags;
- Superb vertex resolution for background rejection and for measuring rapid oscillations of the B_s, as well as excellent momentum resolution for reconstruction of B hadron invariant masses;
- An excellent particle identification system to determine whether particles are pions, K mesons, protons, electrons, or muons;
- Ability to reconstruct photons with high efficiency, low background, and good position and energy resolution in the busy environment of a hadron collider;
- For all detectors, the ability to survive the radiation environment of the Tevatron without significant reduction in efficiency or increase in background over a long period of time; and
- A very high speed, high capacity data acquisition system.

Driven always by our physics goals, we have selected technologies that either have proven track records or are being developed by large groups for other HEP experiments. In the area of triggering and data acquisition systems, we have used commercially available components where ever possible.

Here we describe the status of each of the BTeV detector systems:

- **Analysis Magnet:** The magnet already exists. It needs a pole piece shim, which is already designed. There is a plan for disassembling the magnet, moving it to C0, and reassembling it. This project could have been started 2 years ago and can easily be completed in less than a year.
- **Pixel Detector:** The electronics readout chip, which is designed in 0.25 micron radiation hard technology, is in good shape. A full function readout chip is done and has been successfully operated. The sensors are commercial, and are similar to those used by ATLAS. The vacuum and cooling system is still not final but is well along and is expected to take a few more months of engineering effort and testing to finalize. The design of the cooling system was changed in response to the Temple review where the large number of vacuum-liquid joints were a concern. Our new system is based on cold thermopyrolitic graphite fingers, cooled by liquid nitrogen tubes made from joint-free stainless steel tubing and located well outside the detector acceptance. Cabling and high density interconnects have been prototyped.
- **Forward tracker**
    - –**Straws:** We now have extensive experience with straws. Mechanical assemblies have been completed, prototypes have been made and are ready for beam tests. Splicing techniques have been studied and are being finalized. No problems are expected. The straw tubes are very similar to the ATLAS design. Ageing tests have been done with sources. The last phase of the electronics mounting is not complete. The design of TDC, not considered to be difficult, is just starting.
    - **Microstrips –** a company in Italy is designing and prototyping the support structure. The electronics design is being done by a Milan-FNAL collaboration, and is proceeding rapidly. Sensors are single-sided and like CMS sensors. Electronics is a simple amplifier-shaper-discriminator.
    - **The support interface** between straws and strips not final. Either strips will be mounted on straws or will be independent. This is not yet settled but is not a big problem. There are workable designs for both solutions.
- **Ring Imaging Cerenkov Counter**
    - For the detectors there are two possibilities: a BTeV-developed Hybrid Photodiode (HPD) array, for which prototypes have been completed and tested and Hamamatsu MultiAnode Photomultipliers (MAPMTs). The MAPMT solution was initially rejected for cost and technical reasons. However, the cost is now reduced and dead regions between adjacent pixels are reduced making this system competitive. The two detectors present different electronics challenges. This is a good situation since there are two acceptable solutions. Cost and operational considerations will determine the final choice.

- Electronics – prototypes were done for the HPD’s by a collaboration of Syracuse University and the electronics company, IDEAS, in Norway . Prototype electronics is being finished for the MAPMTs by the same group.
- Gas vessel – The design is done.
- Mirrors – Several options are being evaluated. The tradeoff between cost and material budget is the main issue.
- Gas system – The conceptual design is done. It is relatively simple.

- **Electromagnetic Calorimeter**
  - Crystals from several vendors have been tested. Visits and discussions about costs have taken place. Actual BTeV shaped crystals have been made.
  - Energy and position resolution with PMT readout have been studied in a testbeam at Protvino and results have been published [hep-ex/02090055].
  - Extensive studies of radiation damage have been completed in a testbeam at Protvino and the results have been published [hep-ex/0210011]. $PbWO_4$ crystals can handle our radiation load.
  - Extensive studies of calibration systems have been carried out but are continuing.
  - The mechanical support is designed and a 20% scale model has been built and tested.
  - PMT stability issues are being addressed.
  - The PMT base and HV systems are being designed.
  - The pulse height will be digitized by a QIE chip. The existing chip needs some modifications. BTeV requirements have been defined and approved and design work has begun.

- **Muon Detector –** There has been a substantial prototype effort, with many subunits, called “planks” already constructed. Production studies have been done. One test beam run has already been carried out at Fermilab and preparations are complete for a final test beam run. Assembly issues in the C0 hall are being addressed by means of a scale model. Electronics requirements are finalized. The detector currently uses the ASDQ chip. These chips work fine but may have to be redesigned in a more modern technology by the time we are ready (and able) to procure them.

- **Trigger and Data Acquisition**
  - There is now a complete prototype of the Level 1 Trigger DSP board. The actual Level 1 trigger algorithm has run on it.
  - The DAQ has been reconfigured into data highways (most likely 8 highways). This permits the use of a switch based only on commercial components and eliminates the original custom switch and much associated software development. The event builder is now based completely on standard network components.
  - The design of the buffer memory board for the DAQ has been completed

- Funding has been obtained from the NSF to develop a distributed, hierarchical fault management system to assure that the trigger is working properly, and to do self-diagnostics and automated error recovery. The project is a year old and significant software development has already occurred . [See http://www-btev.fnal.gov/public/hep/detector/rtes/ .]

From the above, it should be clear that all major problems have been successfully dealt with. Much engineering design has already been done, but much remains to do. Key issues such as the Pixel detector read out chip, and a demonstration of its radiation hardness, the Level 1 trigger algorithm, the photon detectors for the RICH, and the qualification of vendors for production of the Lead Tungstate crystals for the EMCAL have all been resolved.

The BTeV project is in an advanced state of readiness. The experiment was given scientific approval after a rigorous review by the Fermilab Physics Advisory Committee in 2000. Continuing R&D led to refinements in the design, and budget pressures led to a descoping which reduces costs but preserves BTeV's position as the best B experiment that will be running towards the end of the decade. Fermilab has already completed a review by their Office of Project Management (Temple review), which demonstrated that the project was close to being ready for a baseline review by the Office of Science (Lehman review). The collaboration is working on a Technical Design Report. The experiment can be built and ready to operate by 2008.

Below, we show several pictures of various aspects of the BTeV R&D program to indicate the progress on the detector components.

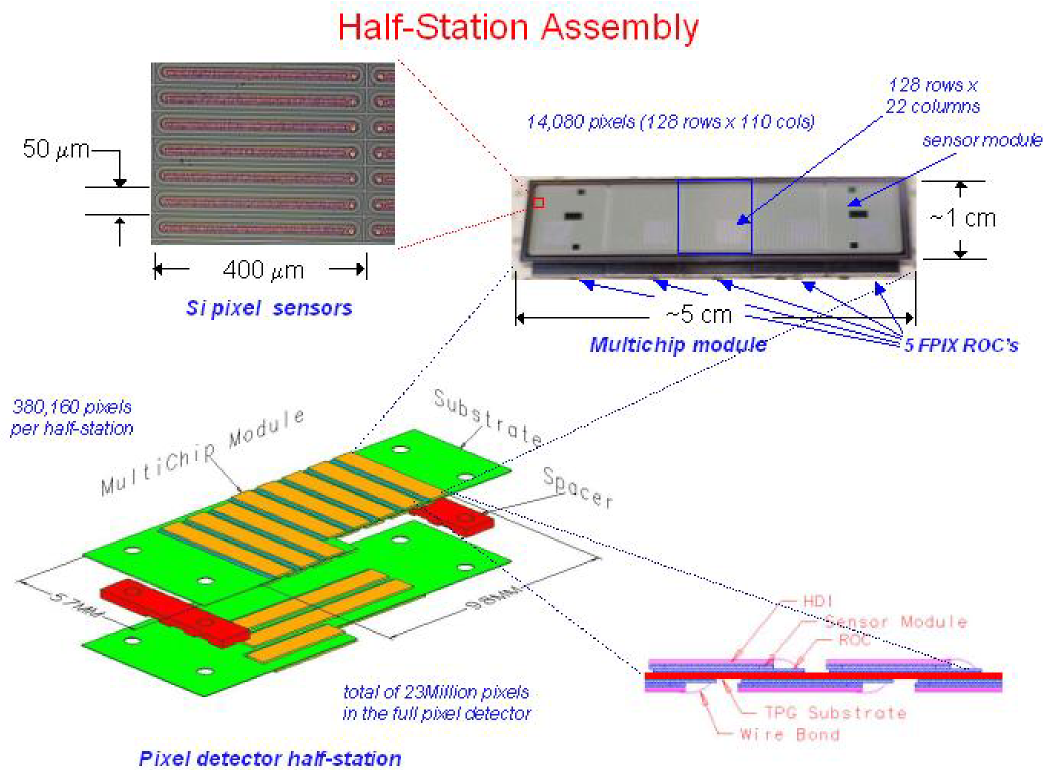


Fig. 1: A representation of the pixel detectors. Upper left shows the actual blowup of a pixel sensor chip. Upper right shows a multi-chip module holding a row of 5 chips. Lower left shows how the multi-chip modules are arranged to make ½ of a plane. The lower right shows how a single detector is built from a sensor (purple) to custom readout chip (green). The connections from each pixel to each "readout cell" is via an individual "indium bump bond". The High Density Interconnect or HDI (yellow) carries signals from the pixel detector to the trigger and data acquisition system.

Fig. 2: Photo of the prototype of the vacuum system for the silicon pixel detector

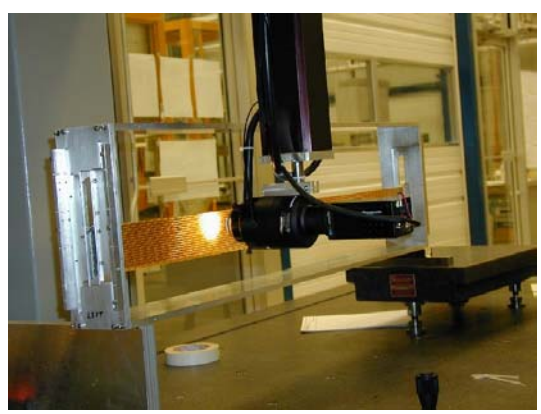


Fig. 3: A prototype straw detector being measured for straw placement accuracy. A wire runs down the center of each straw. A charged particle passing through the straw makes a signal on the wire.

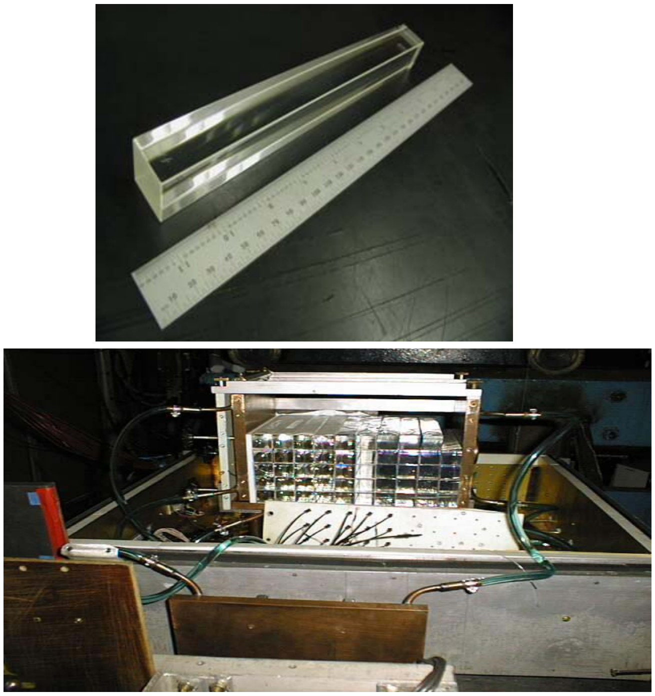


Fig. 4: Top: a lead tungstate crystal. Bottom: A stack of crystals with PMTs on the back, being installed in a temperature controlled box at the electron beam in Protvino for testing

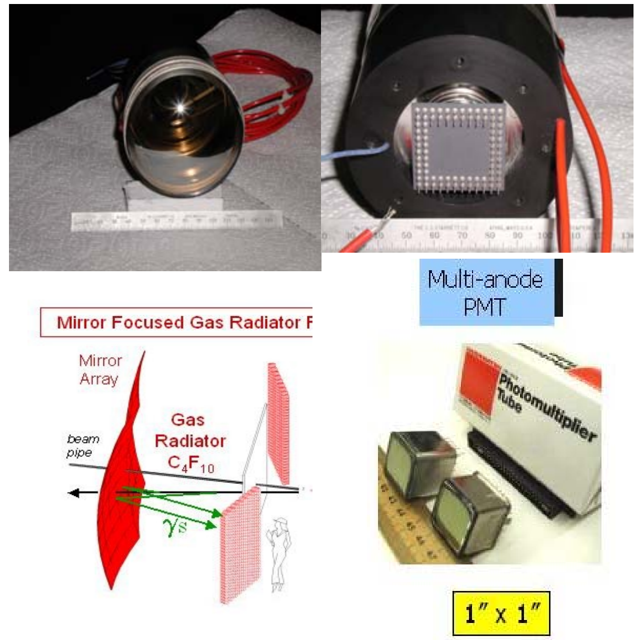


Fig. 5: Lower Left: A schematic of the RICH. Particles enter from the right and radiate Cherenkov photons. They reflect off the mirror array and are detected in sensor planes to the right. Top Left: A HPD with 163 pixels. Top Right: Pins for the signals coming through the glass to a readout board. Lower Left: An alternative sensor, a 4X4 multi-anode PMT

Radiation Hardness of the BTeV Pixel Detector

Although this question is addressed to the "upgrades", we nevertheless provide information on the radiation hardness of the BTeV pixel detector to show the effort that we have put into the detector design. Studies have also been carried out for the forward tracker and the electromagnetic calorimeter, the other susceptible elements in BTeV[1].

1. Radiation Levels

We have done a detailed simulation of the expected radiation levels for the whole BTeV detector and the experimental area. The luminosity used in the simulation was 2×10^{32} $cm^{-2}s^{-1}$. The Pythia generator was used to generate minimum bias events, which served as input particles for the MARS code. The full BTeV geometry file was used, including the location and amount of material in the various subsystems of the detectors, the dipole magnet, and the compensating dipoles. The charged hadron fluence distribution for the BTeV detector is shown in Fig. 6 and the distribution in the pixel region is plotted in Fig. 7. We have also looked at other particles such as

[1] Information about radiation hardness of the electromagnetic calorimeter and the forward straw tracker can be found on the BTeV P5 web page.

neutrons, gammas, electrons, and muons. In the pixel region, the fluences due to these latter particles are more than an order of magnitude less than that from the charged hadrons. As one can see from Fig.7, it is expected that the innermost region of the pixel detector will receive a fluence of 1 x 10^{14} particles/cm^2/year.

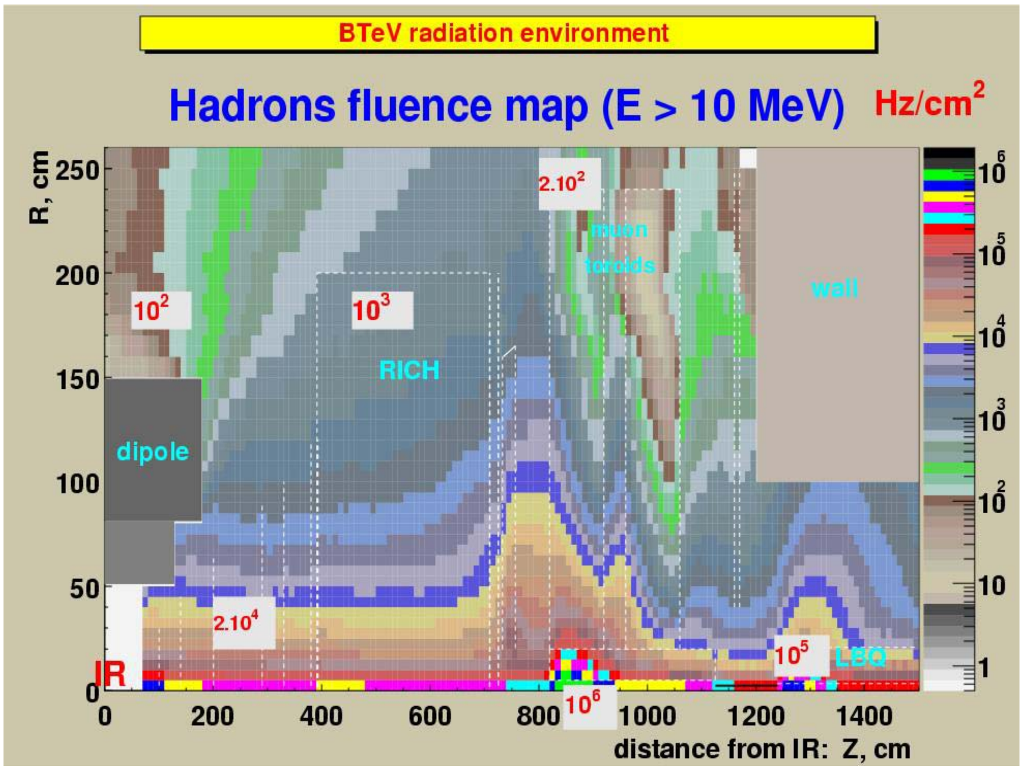


Fig. 6: Fluence distribution for the BTeV detector ($cm^{-2}s^{-1}$)

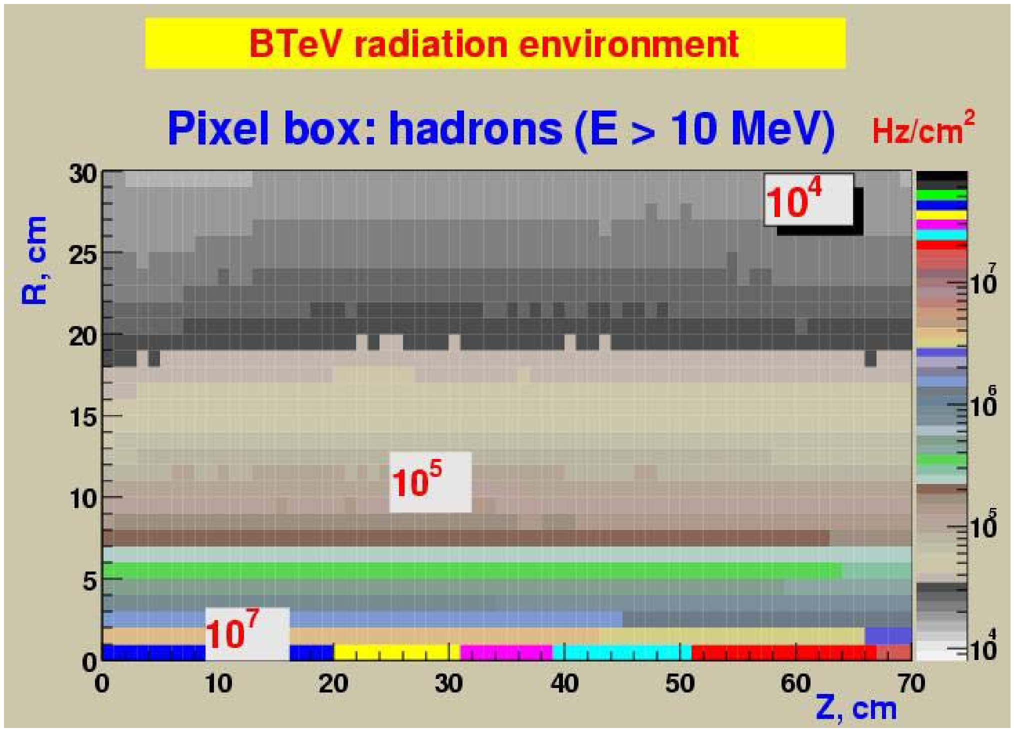


Fig. 7: Fluence distribution due to charged hadrons in the pixel region ($cm^{-2}s^{-1}$)

2. Radiation Hardness Testing of the BTeV pixel detector

The significant radiation environment in which we plan to operate our detector means that all components of the pixel system have to be radiation hardened. We have put the radiation hardness issue as an important guideline since the beginning of the R&D and design of the BTeV pixel detector.

The silicon pixel sensors are based on $n^+/n/p^+$ technology as developed by LHC experiments. Following the conclusion from the CERN RD48 collaboration, we will also use oxygenated silicon wafers of low resistivity as the starting material for the sensors. The pixel readout chips are manufactured with deep sub-micron (0.25 μm) CMOS technology, an inherently radiation-tolerant process, once enclosed-geometry transistors and appropriate guard ring designs are used.

Irradiation tests have been performed up to 0.6 x 10^{15} 200 MeV protons per cm^2 on our sensors (about 20 MRad) and up to 2 x 10^{15} 200 MeV protons per cm^2 (equivalent to 87 MRad) on our readout chips. These tests show acceptable operation of sensors based on current and capacitance curves vs applied bias voltage in terms of leakage current, required depletion voltage, and breakdown voltage. Fig. 8 shows the dependence of the full depletion voltage on the proton irradiation fluence for a few pixel sensors. At a fluence of 0.4 x 10^{15} protons per cm^2, the full depletion voltage is still rather low, even lower than the value before irradiation. This result, together with the fact that the breakdown voltage (typically above 300 V) is still high compared to the full depletion voltage after irradiation, means that the BTeV pixel detector can be fully depleted without excessively high bias voltage even after years of operation at the design luminosity.

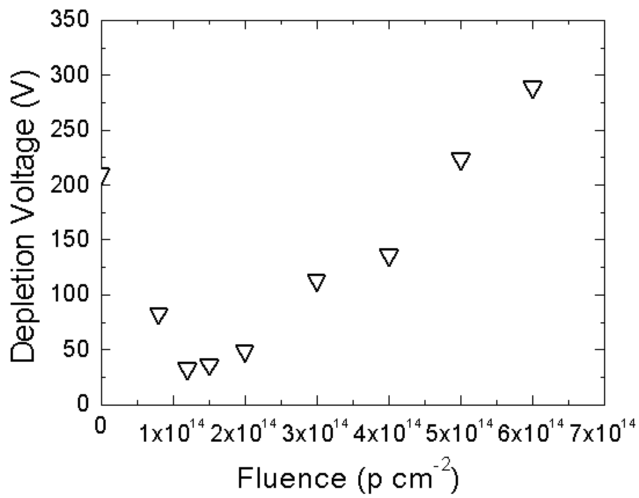
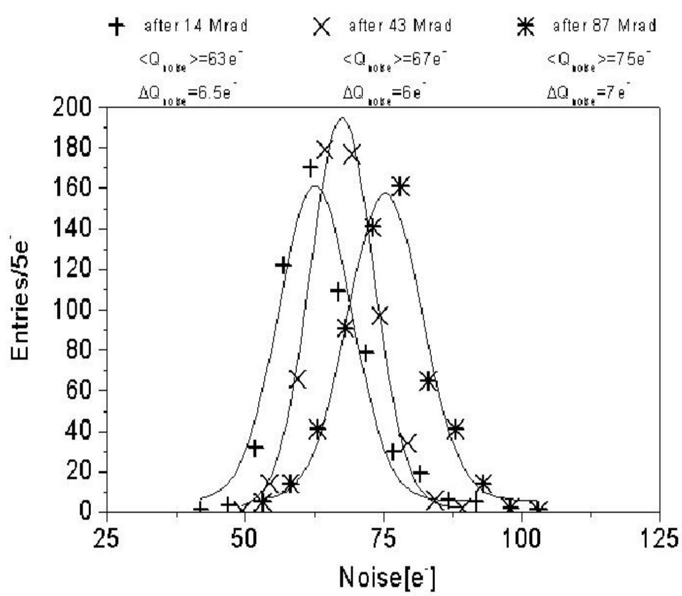


Fig.8: Full depletion voltage as a function of the proton fluence for prototype BTeV pixel sensors

The readout chips in deep sub-micron technology appear to be even more radiation-hard. After 87 MRad, a dosage that is much higher than expected for 10 years of running, the prototype pixel readout chip shows only minor changes in noise, and no increase in discriminator threshold dispersion (Fig. 9).



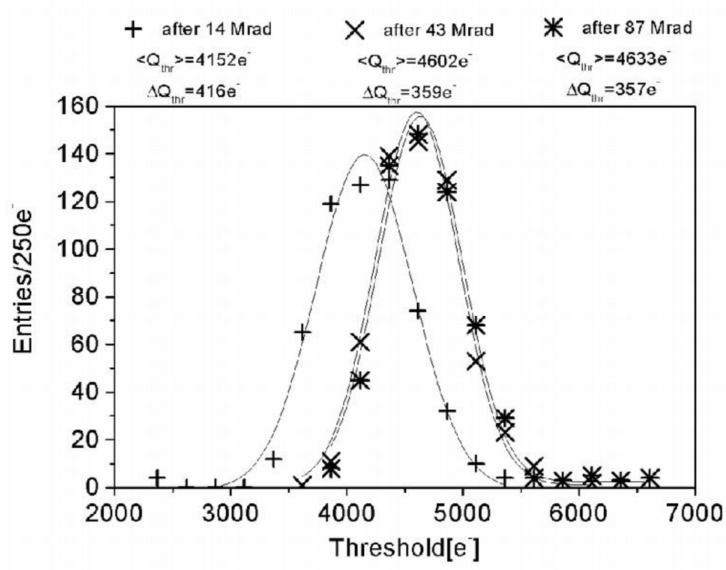


Fig. 9: Noise and threshold dispersion of BTeV pixel readout chip prototypes after heavy irradiation.

In December 1998, when we made the decision to implement the pixel readout chip in a commercial 0.25 micron CMOS process, it had been established, by R&D at CERN, that deep submicron CMOS circuits could be at least as radiation tolerant as circuits implemented in explicitly radiation hard CMOS processes. However, the sensitivity of these circuits to single event effects had not been measured. We therefore gave a high priority to measuring single event effects as soon as our first prototype circuits were available in the summer of 1999. Over the next 2½ years we made a series of measurements using the 200 MeV proton cyclotron at Indiana University. No catastrophic event (gate rupture or latchup) was observed in any of these exposures. This established that the rate of catastrophic single events would be small enough to be acceptable for BTeV. Somewhat to our surprise, and to our great satisfaction, we found that our prototype circuits were able to operate normally in a rather high intensity proton beam – high enough intensity that we were able to make statistically significant measurements of the single event upset cross sections for a number of different types of registers and flip flops. These cross sections ($1 - 6\times10^{-16}$ cm^2 for 200 MeV protons) are all small enough that redundant logic is not required for most of the readout chip subcircuits. Our readout chip architecture allows most internal settings to be non-destructively read out on a control pathway at the same time as hit data is being read out from the chip at high speed. During operation, the pixel data combiner boards will continuously look for evidence of single event upsets, and reset registers that have been upset. We estimate that, at a luminosity of 2×10^{32} $cm^{-2}s^{-1}$, approximately two control register bits will be upset in the entire pixel detector per hour, that single event upsets will cause about 1 bit error per hour in the data read out, and that no more than 10 pixel kill registers (out of 23 million) will be upset.

These irradiation results will be augmented with charge collection and other tests in a test beam at the Fermilab Meson Test Beam Facility as soon as it is available. Finally, we have started and will continue to test all components (bump bonds, high density interconnects, adhesives, etc.) in high radiation environments before final certification for use in the pixel detector. We are confident that the BTeV pixel detector will remain fully operational for well over 5 years of running at the design luminosity of 2×10^{32} $cm^{-2}s^{-1}$.